NIPER-195
Distribution Category UC92

Status Report

FEASIBILITY OF USING NUCLEAR MAGNETIC RESONANCE IMAGING AND COMPUTED TOMOGRAPHY FOR DETERMINING RESIDUAL OIL SATURATION

Project BE8, Task 7 in FY86 Annual Plan dated May 1986

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September 1986

Work performed for the
U. S. Department of Energy
Under Cooperative Agreement
DE-FC01-83FE60149

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SUMMARY

The principal objective of project BE8, Residual Oil Saturation and Measurement and Estimation Improvement is to improve the accuracy of resistivity log measurements by developing calibration parameters for Archie's equation or similar interpretation techniques, as functions of reservoir rock type and reservoir conditions. Two other objectives of this project are:(1) to study the feasibility of the use of nuclear magnetic resonance imaging (NMRI) and computed tomography (CT) for residual oil saturation (ROS) determination and (2) to estimate the magnitude of errors in oil saturations resulting from inaccuracy in the analysis of resistivity log data. Several tasks have been proposed to achieve these objectives. The purpose of task 7, which is the subject of this report, is to explore the feasibility of the use of NMRI and CT for ROS determination.

In this report, results from water phase (1 percent NaCl) saturation measurements using NMRI and CT techniques on 1.5-inch diameter, 4-inch long Cleveland sandstone cores are discussed. A water phase was used instead of an oil phase for simplicity. Results obtained for the water phase can be extrapolated to the oil phase since water and oil relaxation times in rocks have the same magnitude (in the order of hundred msec). NMRI and CT signals' behavior at irreducible water saturation is considered to be equivalent to signals' behavior at residual oil saturation. Water saturation distributions along the length of the core obtained by these two techniques are also

discussed. Cleveland cores were selected for this study because they provided the highest NMRI signal due to bigger pore size when compared with Bandera and Berea cores.

The limited results available show that NMRI and CT have the same degree of accuracy when measuring fluid saturation and fluid distribution in core samples. CT has immediate applications in coreflooding at reservoir conditions, unlike the NMRI where non-metallic, high-pressure vessels are needed. We recommended this type of study to be continued for a better understanding of applications of NMRI and CT for fluid saturation and fluid distribution measurements.

INTRODUCTION

A variety of methods for measuring fluid saturations in porous media have been developed: gravimetric, volumetric, electrical resistance, gamma ray attenuation, neutron, radioactive tracers, x-ray absorption, and microwave attenuations. Most of these techniques can be used to measure residual oil saturations which range between 30 and 50 percent but none can provide a three-dimensional picture of fluid saturation and fluid distribution in a core sample as NMRI and CT techniques can.

The NMRI technique relates fluid saturation to magnetic resonance relaxation. The images produced are essentially density maps or pixel values (NMRI signal proportional to magnetization) which are related to the number of protons (principal isotope of hydrogen) in the core sample and their NMR relaxation times. The CT technique is a less cumbersome technique which relates fluid saturation to the absorption of electromagnetic radiation (function of atomic number). It is less cumbersome since the absorption of x-rays is the principal parameter. CT images both rock matrix and pore fluids, whereas NMR images only mobile fluids and the interactions of these mobile fluids with the confining surfaces of the pores. The physical properties imaged by the two techniques are complementary.

NMRI and CT technologies are well established in the field of medicine. For example, NMRI provides physicians with an unprecedented ability to discriminate between various tissues and their pathology. Application of NMRI and CT in the petroleum engineering field has just begun.

This report presents results of a feasibility study of the use of NMRI and CT for ROS determination. A brief summary of the NMRI and CT theory and equipment is presented first, followed by experimental procedure and discussion of results and conclusions.

NMRI TECHNOLOGY AND NMRI APPARATUS

Nuclear magnetic resonance (NMR) spectroscopy has been used since 1946 to study atomic and molecular structure.[1] In the early 1970's, two developments, the production of very homogeneous and intense magnetic fields by superconductive magnets, and the introduction of Fourier transform techniques for data processing greatly enhanced the power of NMR spectroscopy. Not until 1973 was the possibility of using NMR for imaging proposed.[2]

NMRI is the application of a controlled sequence of radio frequency (RF) pulses and magnetic field gradients in three dimensions to the standard pulsed NMR experiment to develop a "map" of the NMR spin density as a function of position within the sample. Thus, information about the physical location within the sample of selected nuclei (for example, protons) possessing certain characteristic chemical shifts, or relaxation times (T_1 and T_2), is attainable and can be related to the properties of the sample. Details about the principles of nuclear magnetic resonance imaging have been reported.[3,4,5]

NMRI appears to be a promising technique for identifying distribution of different fluids (surface adsorbed water, bulk water, surface adsorbed oil, bulk oil, etc) in rock samples. A particularly useful application would be for evaluating the effect of core cleaning on the distribution of these fluids. NMRI may also be useful in identifying heterogeneities (e.g. fractures, cross beds and shale breaks) and for describing distribution and displacement of fluids resulting from these heterogeneities.

The attractiveness of the NMR method for investigating the nature of rock-fluid interactions and monitoring changes in these interactions arises from the number of different NMR parameters available for investigation, such as variations in chemical shift between fluid types, changes in spin-lattice (T_1) and spin-spin (T_2) relaxation times, and from the nondestructive nature of the experiment, permitting successive experiments on the same sample.

In this study, an NMR scanner was used in conjunction with a laboratory-built solenoid receiving coil.[6] A Picker MR VISTA - 2055 scanner, was operated at 0.5 Tesla with the proton resonance frequency of 21.3 MHz. Other components of the scanner include a RF pulse synthesizer, a wide band RF linear amplifier (2kW), x, y, and z gradient drives and amplifiers, active magnetic field shimming drive, a magnet power supply (used once with the initial power on), cryogen level detectors for liquid nitrogen and liquid helium, and a digital computer. The current software is Picker MR4/TABF which includes 2 dimensional Fourier transform imaging with multiple slice capability. The slice thickness is 10 mm, spatial resolution 1 mm.

CT TECHNOLOGY AND CT APPARATUS

CT is a method employing a computer tomography (CT) scanner to scan a sample to create x-ray photographs of cross sectional slices of the sample so that its internal anatomy can be displayed. The technique involves rotating an x-ray source and diametrically opposed detectors synchronously about the sample to be observed. One-dimensional projection of x-ray absorption at different angles is collected. A cross-sectional slice through the sample is constructed by computer. A three-dimensional image is reconstructed from sequential cross-sectional slices taken as the sample is moved through the CT scanner.

CT technique is being used for an increasing number of petrophysical and reservoir engineering applications such as core analysis studies of fluid flow in porous media and reservoir rock description.[7-9]

The CT scanner used in this study is a Siemens Somatom 2, a third-generation scanner with a tungsten target, aluminum filter, pulsed x-ray tube, and a Scintillarc detector. The peak acceleration voltage is 125 keV. Deconvolution of the 2 mm beam line integrals are performed with Siemens BSP 10. The slice thickness is 4 mm, spatial resolution 0.5 mm.

EXPERIMENTAL PROCEDURE

Cleveland sandstone cores 1.5-inches diameter and 4-inches long were cut and dried. NMRI and CT scans of the dry core were obtained. Cross sectional images were obtained along the core length, in increments of 10 mm and 4 mm between successive images for NMRI and CT, respectively. The x-ray linear attenuation coefficient (CT) and pixel intensity (NMRI) were obtained for circular elements (about the size of the core cross section) for each cross sectional image.

The spin-echo radio frequency (RF) sequence[10] was selected for all NMRI experiments based on successful results obtained in medical NMR which uses this sequence to distinguish between lipid and water tissues. Proper echo time (TE equal 40 msec) and repetition time (TR equal 500 msec) were selected so that the image obtained was spin density (proton density) weighted.

Assumptions made in the pixel density measurements are (1) the RF sensitivity of the solenoid coil in the region of the sample is measurable from the control experiment using a vial of uniform aqueous liquid; (2) the pixel intensity as a function of spin density, T_1 and T_2 conforms to the I(SE) equation derived from the Block equations;[11-12] and (3) contribution of chemical shift artifacts to the image contrast at present field strength (0.5 Tesla) is negligible.

Cores containing fluids were scanned following the same procedure as used for dry core. For the CT, a straight line calibration was established based on the attenuations of the central portion of dry and fully saturated cores because Beer-Lambert's law predicts a linear relationship between attenuation and saturation of absorbing species.[13]

Various brine saturations were attained by displacing the brine with nitrogen and simultaneously injection of brine (steady-state technique). Brine saturation ranged from 24 to 100 percent. The flow rate of nitrogen was changed from 50 to 1,200 ml/min and the brine flowrate from 0.1 to 5 ml/min. A gravimetric technique was also used to determine average water saturation. After steady-state was reached (constant pressure drop along the core sample) for each brine saturation, the cores were scanned with the NMRI and CT apparatus.

The pixel intensity of the central portion of the core at different brine saturations was used to establish the calibration curve for the NMRI techniques. It was found that the relationship between pixel intensity and fluid saturation is not linear. This may mean that the spin echo sequence used in these experiments was not only spin density weighted but also T_1 and

T_2 weighted as well. Further study is required to explain such behavior. For both techniques (CT and NMRI), it is preferable to develop a calibration curve for each position along the length of the core. This was not considered necessary for this study since the Cleveland core is a relatively uniform core.

DISCUSSION OF RESULTS

Pixel intensities and attenuation coefficients were converted to brine saturation profiles using the calibration curves. These calibration curves were developed as previously described in this report. The results are shown in figures 1 and 2.

A brine saturation lower than 50 percent could not be achieved on core used for NMRI experiments. The reason for this anomaly could not be identified. The same behavior observed at 50 percent brine saturation is expected for irreducible brine saturation (around 24 percent), as indicated in figure 1.

Smooth profiles were obtained by the CT techniques at all saturations and by the NMRI at saturations lower than 60 percent, which is in part attributed to the large core area involved in the measurement, e.g., 4.5 cm^2 for CT and 6.1 cm^2 for NMRI. For the CT technique, brine saturations measured are within 5 percent of brine saturations measured by a gravimetric technique. NMRI measurements at low brine saturations are also within 5 percent of gravimetric measurements (see numbers on curves on figure 1). Considerable descrepancy is observed at high brine saturation, especially at 100 percent.

The saturation profile by the NMRI technique does not show smooth profiles at high water saturations. With regard to these results, several possible interactions may contribute to this behavior. If the effect of a single

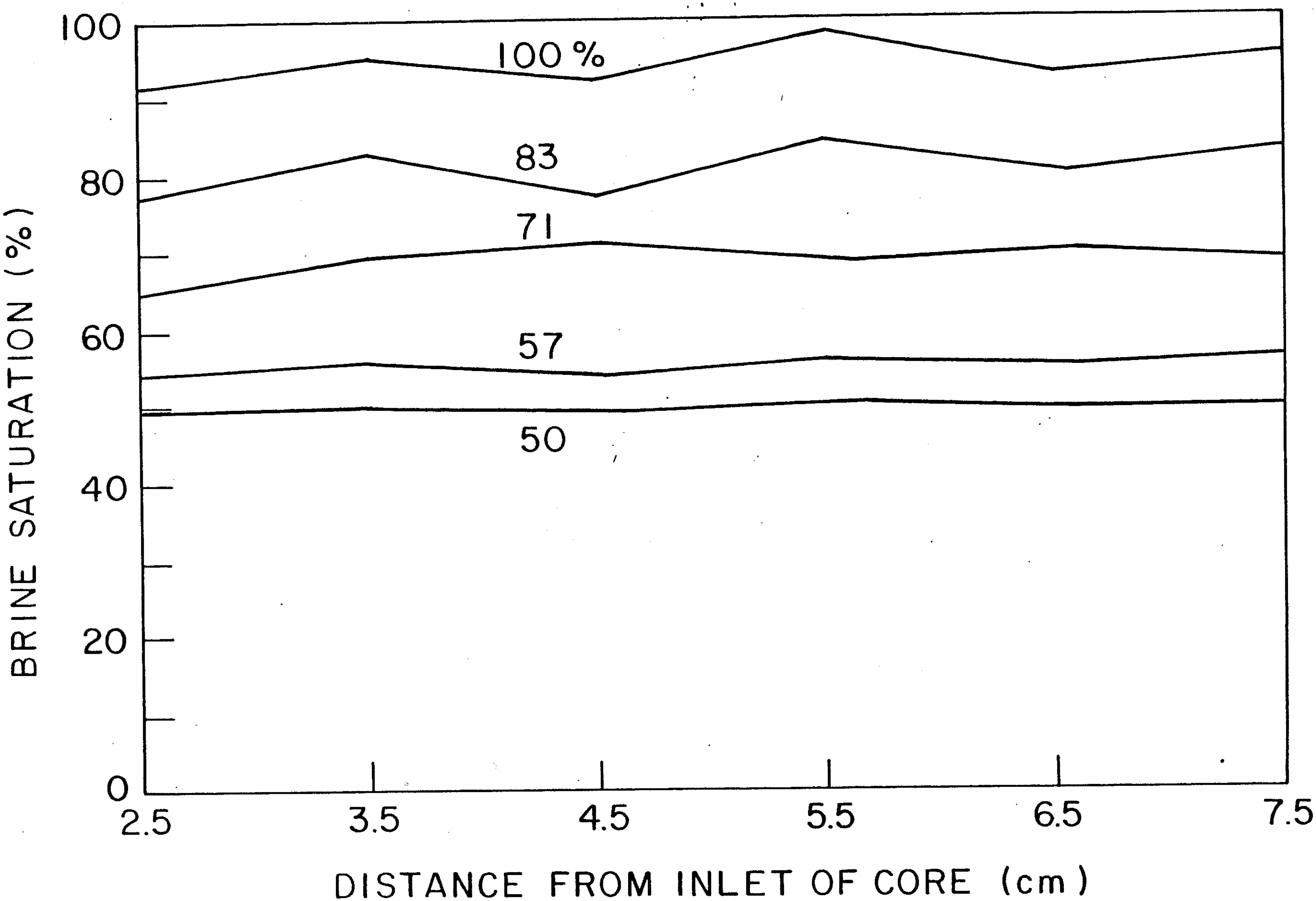

FIGURE 1. - Saturation profiles along Cleveland core--NMRI technique.

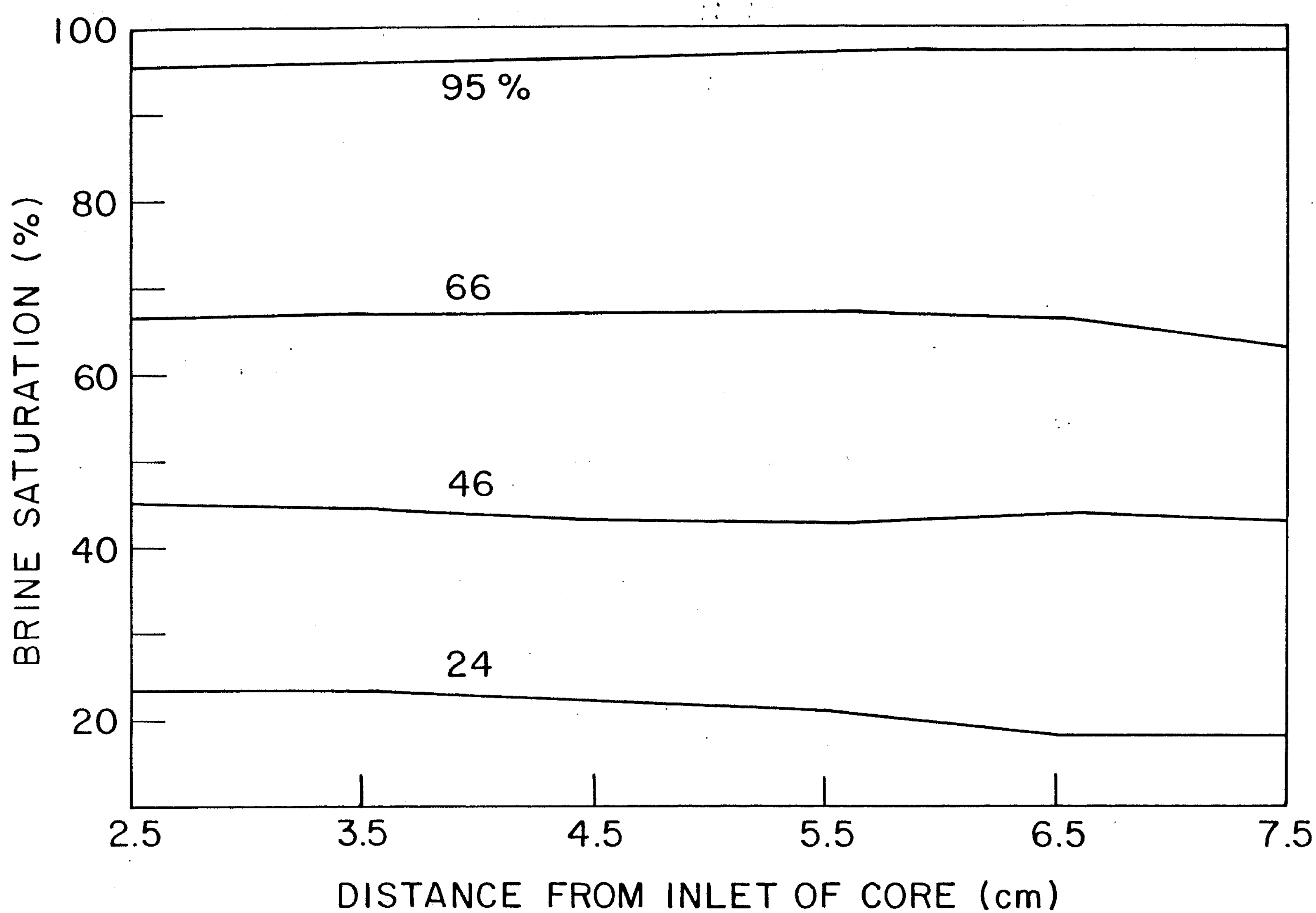

FIGURE 2. - Saturation profiles along Cleveland core--CT technique.

paramagnetic ion species is dominant, a straight line can be expected; however, water may behave differently when surrounded by paramagnetic ions (i.e., form many cages around the water molecule), water in the outer periphery of the cage and bulk water may also exchange protons, and/or water may bind noncovalently to electronegative atoms other than paramagnetic ions present in the pore. All of these conditions above may contribute to heterogeneities in the correlation times which yield results shown in figure 1. The presence of a high percentage of bulk water (at high fluid saturation) appears to cause the fluctuations since these effects are less pronounced at low brine saturations (almost no variation in the profile is observed). The effect of each one of these variables on fluid saturation measurement by NMRI needs further study.

Results are expected to be improved when different calibration curves are used for each position along the length of the core. These calibration curves will account for differences in pore and throat sizes and paramagnetic ion content (Fe^{+2} or Mn^{+2}) in the core samples which affect proton relaxation time T_1 or T_2 (pixel intensity).

CT technique is considered a direct method, whereas the NMRI technique is not. The advantage of the direct method is that a gravimetric technique is not required to construct the calibration curve. The gravimetric method is not considered accurate since its measurement represents average saturation throughout the core.

CONCLUSIONS

- NMRI and CT techniques can provide saturation profile information that can be used to determine ROS after application of an EOR process or to help during the development of an EOR process.

- A calibration curve should be developed for each position along the length of the core for which predictions of fluid saturations are needed during multiphase flow processes. This requirement has more importance for NMRI than for CT.

- Differences in fluid distribution along the core sample at a particular brine saturation affect NMRI measurements. This effect is more pronounced at high brine saturations. Studies are underway to learn more about this behavior of NMRI signal from rock samples.

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(EEH) SR-BE8Tk7